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TC-93: EXPERT SYSTEMS FOR BUILDING MATERIALS AND STRUCTURES

Expert/knowledge based systems for materials in the construction industry: State-of-the-art report

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1. INTRODUCTION

Artificial intelligence, a branch of computer sciences, comprises machine vision, natural language, robotics, and expert systems [1]. Many agree that the expert systems area has advanced furthest and achieved the most success in applying artificial intelligence methods to real-world problems. Two examples of operational systems in use today are Windloader [2], an advisory system designed to assist in determining wind loads on structures, and Highway Concrete (HWYCON) [3], designed to assist in the diagnosis of, selection of materials for, and repair and rehabilitation of highway concrete structures. Successes in using expert systems technology to develop practical applications for the construction industry are relatively few, compared with advances in computer aided design, real-time control, and data analysis. Several reasons for this can be identified:

1, user attitude... because the promise of the technology has failed to deliver;

2, constraints in acquiring knowledge about a subject; and

3, lack of easy-to-use development tools

Expert systems are also referred to as knowledge based systems or decision support systems. The definition often given of an expert system states that there is a heuristic component that can operate on or use knowledge to make recommendations, draw conclusions, and/or propose a hypothesis. It is also stated that it can act as an expert, and possess the ability to learn. In reality, systems at present do not possess this learning component. An accurate definition of how an expert thinks has yet to be developed. This does not mean that expert systems technology cannot be used successfully to aid in decision making for many applications in the construction industry. Their application has been applied successfully to the design of structures and structural components, distress identification and diagnostics of the failure of structures and materials, repair and rehabilitation, and in project planning. Advances in microcomputer performance, the development of improved tools for building expert systems, and a greater awareness of the potential of the technology will probably promote their use. Expert systems will not replace the expert. They can assist those who are less knowledgeable in the subject domain in using the knowledge of higher-level experts. A successful expert system is one that mimics the way an expert(s) would apply his problem-solving abilities in making a recommendation or drawing a conclusion, with a high degree of accuracy. Expert systems differ significantly from other computer program architectures because they separate what is known about an application, called domain knowledge, from the logic that controls how the knowledge is used, known as inference procedures.

This report is the result of a survey of many of the existing prototype and operational expert systems that have been developed for the construction industry. The report includes those that are representative of the areas of the construction industry that have received the greatest attention from expert system developers. A description of the methods used to acquire, represent and process knowledge is included. Also, a brief overview of the most mature and significant systems is presented. Finally, the potential for the application of expert systems technology is discussed. Appendix A is provided to assist the reader in understanding expert systems terms used in the report, and Appendix B is a bibliography providing information on many of the systems revealed during the development of this report.

2. EXPERT SYSTEMS: OVERVIEW

2.1 Expert systems defined

Expert systems have been defined differently by many authors. Feigenbaum, one of the earliest developers, defines an expert system as "An intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution" [1]. Although this definition can be interpreted differently, for example, the level of human expertise embodied in the system, it does identify the two basic components, knowledge and inference. Fig. 1 illustrates a simple configuration of an expert system that includes these components.

2.2 Knowledge acquisition and knowledge forms

The knowledge-base component of an expert system contains what is known about the subject area, called the knowledge domain. The knowledge-base usually addresses only a small portion of the knowledge domain, such as the identification of distresses and diagnosis of failure in bridges. This is typical of expert systems developed for the construction industry. The larger the knowledge domain, the more difficult it is to develop and to maintain expert systems. Therefore, the most successful systems have a narrow knowledge domain.

The process of acquiring the knowledge base is the most difficult task in developing an expert system. High level experts use heuristics in solving problems. Heuristics represent facts and rules of thumb that are generally accepted, but in some instances may not always be true. Cloning a human expert's knowledge is also difficult because they may not be able to explain the reasoning behind their knowledge or beliefs. As a result, expert systems are often narrow in scope and address a specific set of problems. An example of the knowledge acquisition process is described by Hanna [4], relating to an expert system for the selection/design of a formwork for the construction process.

In addition to the expert's day-to-day problem solving ability, knowledge from published standards, guidelines of accepted practice, and explanatory text describing the specific domain area and methods are also used in developing the expert system knowledge base. Robust systems utilize this knowledge extensively in support of decision making. Future expert systems will be integrated systems containing computer based models, databases, etc. Fig. 2 shows an example of a more advanced expert system implementation for a highway structures application.

2.3 Knowledge representation

Incorporating knowledge types other than facts and rules-of-thumb into expert systems is increasingly becoming the state-of-the-art. Visual knowledge such as graphics, photographs, and drawings are being used to provide the end user with examples of distresses, repair procedures, or the characteristics of a structural component of a building. This is an important feature in a system because it can reduce the interaction between the end user and the expert system by eliminating a number of questions required by the system. Information contained in

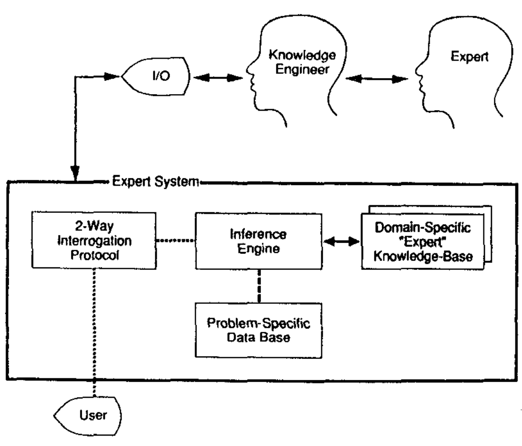

Fig. 1 Simple expert system configuration.

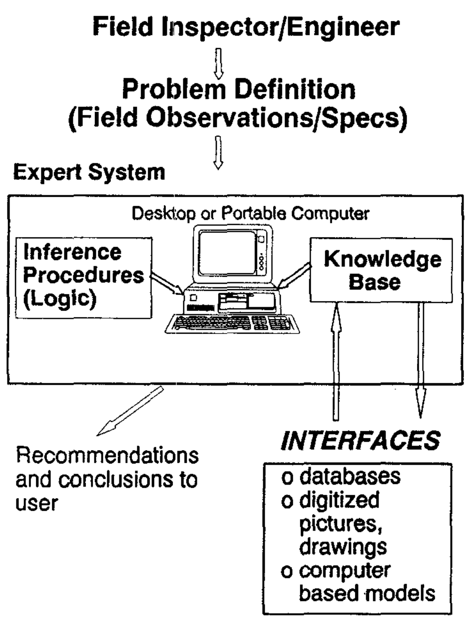

Fig. 2 Advanced expert system configuration designed for highway structures application.

database management systems represent another form of knowledge. This information can serve to describe the characteristics of graphics and images, represent observations from field inspections, or can supply the expert system with simple data elements needed to achieve a goal.

Most expert systems that have been developed to date are production systems. Knowledge is represented in the form of IF-THEN-ELSE production rules. For example; IF antecedent, THEN take the consequent. The following example, taken from the knowledge base of DURCON [5], gives recommendations on the amount of entrained air for concrete exposed to freezing and thawing conditions.

If: [1] Severe freeze–thaw conditions are anticipated and
[2] The nominal size of aggregate is 3/8 inch
Then: The *percentage* of entrained air should be 7.5

Each production rule in the system represents a single piece of knowledge. Sets of related production rules are used to achieve a goal (e.g., recommend the amount of entrained air). Expert systems of this type involve conducting a session where the systems attempt to find the best goal using information supplied by the user. The sequence of events comprises a question and answer session.

Another form of knowledge representation is the frame- or object-oriented system. In these systems knowledge is grouped in a way an expert normally thinks of the knowledge domain. Objects or frames are represented by classes and instances. The class component defines the object's properties and attributes. The instance contains the knowledge values. Objects can inherit the properties of other objects. For example, a class called 'failure' may be established, and may be divided further into subclasses for materials related distresses and in-service related distresses. The members of these sub-classes share the characteristics and behaviour of the class 'failure'. Object-oriented methods are becoming more popular today, due to the flexibility that exists in drawing relationships between related knowledge and development tools that allow the use of different inference procedures within a single expert system. Perhaps the most significant advantage of using an object-oriented design is the ability to find and change the knowledge base. Expert system shell programs based on an object-oriented design allow the association of objects, their attributes, and instances, and they provide development tools to build systems more easily (e.g., editors, interfaces, and graphical capabilities).

2.4 Inference mechanisms

The inference mechanism part of an expert system determines how the knowledge is to be used. It controls the selection and use of knowledge and facts in the knowledge base and applies reasoning necessary to solve a problem. Normally referred to as the inference engine, an inference mechanism uses procedures that search for problem solutions in either forward reasoning (forward chaining) or backward reasoning (backward chaining). In a forward reasoning search strategy the expert system uses known facts and attempts to reach a goal state by evaluating conditions that relate to a fact, for example an alarm state (see Fig. 3). Forward reasoning inference is said to be data driven or event driven because it is triggered by known facts or specific events that occur.

A backward reasoning strategy starts with a conclusion and works backwards and attempts to prove the facts, in search of a goal (see Fig. 4). The backward reasoning inference mechanism is the most commonly used. Backward reasoning starts with a hypothesis or goal and attempts to verify it. For this reason, it is said to be goal driven.

Another type of inference mechanism is the

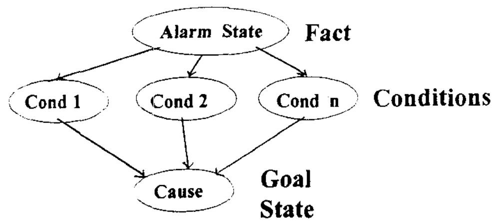

Fig. 3 An example of forward chaining inference.

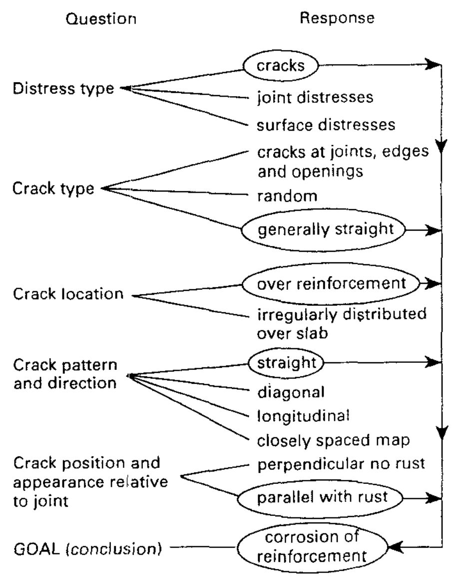

Fig. 4 An example of backward chaining inference.

Table 1 General distinctions between expert systems and conventional computer programs

Expert system	Conventional program
Makes decisions	Calculates results
Based on reasoning	Based on algorithms
Conducive to change	More difficult to change
Can handle uncertainty	Cannot handle uncertainty
Can work with partial information incon-sistencies, partial beliefs	Requires complete information
Can provide explanations of results	Gives results without explanation
Symbolic reasoning	Numerical calculations
Primarily declarative	Primarily procedural
Control and knowledge separated	Control and knowledge interlaced

blackboard architecture. In a blackboard system, a central location is used to communicate among different knowledge sources to keep track of changes made in the problem state. The procedure uses the forward and backward reasoning methods to solve the problem.

2.5 Expert systems versus conventional programming systems

Expert systems differ fundamentally from conventional computer programming systems because they separate the knowledge from the inference procedure. This provides a significant advantage for developers and maintainers of a system. Also, expert systems represent a more powerful implementation of knowledge, compared with conventional programming systems. They possess the ability to give the end user explanatory information and can give the reasons why they are pursuing a certain operation or path. Table 1 shows the significant differences between expert systems and conventional computer programs.

2.6 Expert system capabilities and limitations

Expert systems for construction industry applications are most useful where the knowledge can be represented in a narrow and well-defined knowledge domain. In a complex domain, expert systems are unlikely to contain the complete expertise of the leading domain expert. Expert systems do, however, offer a means of capturing human expertise, and provide an environment which allows that knowledge to improve and expand. Expert systems do not currently posses the ability to learn, and they lack common sense and intuition, although research into the area of neural networks [6] does show promise towards learning capabilities, and these may in the future be components of expert systems.

Advances in computer technology and software architecture have improved the user interface and machine performance. Earlier systems were characterized by an inadequate interface, comprising mostly text input and output. Graphics and images now provide a visual capability to enhance the understanding of the knowledge domain. The performance of expert systems with regard to speed and responsiveness to user questions and answers have also improved. Small desktop and portable computers are now capable of executing practical and useful systems. The most successful applications for expert systems use deductive reasoning methods. These systems can be characterized as advisory systems that give the user conclusions and recommendations as output.

2.7 The development and use of expert systems

Until the mid 1980's expert system developers used primarily the Lisp and Prolog artificial intelligence languages to develop expert systems. The use of these languages required unusually long development time, e.g., 5–10 years to complete a complex system. These languages are used much less today. Most systems surveyed by this report make use of expert system shell programs.

2.7.1 Development team

Developing an expert system requires a high level of the knowledge domain, an expert(s), and a person to organize and translate the knowledge into the language .of the computer, called a knowledge engineer. Although both of these roles may be filled by the same person, systems that are complex in nature will require a different team member for each activity. The reasons for this are the time requirement for developing a system, and the need for the developers to work closely with the user. In any case, the task of knowledge engineering is often tedious, and still requires an in-depth knowledge of the inner workings of computers. Also, many of the domain experts are unfamiliar with the new software engineering tools. It is generally accepted that the most successful systems are developed within the organizations where the system is to be used. An example of this is XCON [7], an expert system designed to configure computers at a major computer manufacturer in the USA. In this environment, the developers work closely with the user since they exist within the organization. This environment also allows the system to achieve maturity, through continuous refinements and updating.

2.7.2 Development steps

The development of expert systems involves: 1, the identification, selection, and organization of knowledge and reasoning; 2, translation of knowledge into a computer readable form; 3, testing the

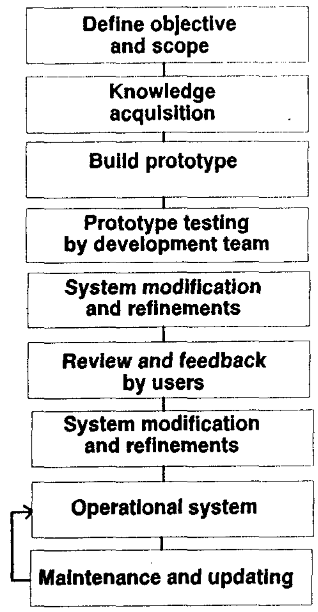

Fig. 5 Steps in developing an expert system.

implementation for accuracy and to make refinements; and 4, preparation of documentation describing the system design and operation. Actually, a production system is never complete. New knowledge must be entered into the system to keep it current. This often requires a significant effort to identify and integrate new knowledge. Fig. 5 shows an example of the steps involved in developing a production expert system.

While the task of knowledge engineering is one of the most critical steps in expert system development, it is also the most time consuming. It is at this stage that the system's objectives, domain knowledge and sources are defined. It will involve many iterations to reach an acceptable representation. Most system developers use human experts during this step. It is important to establish knowledge domain boundaries and not attempt to solve the problems of the universe. Systems can be revised later to include new and expanded knowledge. Many texts exist that describe knowledge engineering activities [8–11]. In addition to expert knolwedge, information contained in guides, published standards and the literature are also used in expert systems development. At least one system, DURCON [8–11], used the American Concrete Institute 'Guide to Concrete Durability, 201' as its knowledge base. The addition of this type of knowledge adds credibility to expert systems. This is because the knowledge contained in a guide has already been agreed upon.

The prototype building and evaluation steps in expert systems development give experts, testers and end users the opportunity for validation and for ensuring that the correct representation of knowledge is accomplished. Since there are no proven methods of testing and evaluating systems, this step is essential. Often these steps are omitted and the system fails to achieve its objective, and development ceases at the prototype stage. Most expert systems surveyed in this report reflect this. Systems that become productive systems require several modifications with feedback from users and evaluators during and following the development stage. Formal procedures are needed to provide a mechanism for maintaining the system. Prerau [12] describes such a mechanism that includes important issues such as technology transfer, organizational roles, training, user acceptance, and deployment.

2.7.3 Expert system development tools

Although the Prolog and Lisp computer programming languages were extensively used in early expert system development, they have become less popular as tools in developing systems. Expert system shell programs are the most popular tools in use today. Unlike their programming language counterparts, shell programs provide extensive editing, debugging, and other development aids, and are more efficient in executing the expert system. Initially, these systems were available on scientific and engineering workstations. They involved a long learning curve to master the system. Now, these systems have been replaced by shell programs that are available on smaller personal computers.

Shell programs provide a development environment that includes a specific syntax for acquiring, representing and using the knowledge. More advanced systems available today offer improved methods for including different forms of knowledge, multiple inference procedures, and extensive interface capabilities with external programming modules, and databases. Table 2 describes the major differences found between computer programming languages and shell programs. Table 3 identifies the most common features found in expert system shell programs available today. Another advantage of using an expert system shell is the speed at which it processes the knowledge. Since most systems are developed using small desktop computers, it makes an economical and responsive system for the user. There are disadvantages in using shell programs. This may be the flexibility for shaping the system (e.g., adapting the knowledge to the inference mechanism). Programming languages offer the developer a tool that can be customized to meet the expert systems objectives. Some shell programs, however, may be designed to address a particular type of application and may offer only one inference method and may restrict the developer in interfacing external programs and different forms of knowledge.

Table 2 Programming languages and shell program differences

Programming languages	Shell programs
Flexibility in programming inference procedures	May have only one inference method available
Source code more difficult to read and modify	Facilities to edit knowledge base and alter inference procedures built-in
May require several steps (e.g., compilations, linking) to generate executable program	Development of executable program is interactive
Often requires special skills specific to AI, expert system programming methods	Current tools require less-specialized personnel
Development time often takes 5–10 years for complex systems	Development time is often half the time required for programming languages
Interfacing different knowledge forms is the responsibility of the user	Interface capabilities exist to integrate different knowledge forms and other computer program modules
Complex systems may require large amounts of computer memory and fast central processors to run the system	Many shells are developed for small desktop computers

Table 3 Common shell program features

More than one inference method available (e.g., backward chaining and forward chaining)
Graphical interface for visual display of knowledge and control of the system
Editors for rules, procedures, displays, and objects
Database manipulation capabilities
Improved capabilities for text searching, animation, and special effects

3. THE APPLICATION OF EXPERT SYSTEMS TO THE CONSTRUCTION INDUSTRY

The application of expert systems to the construction industry has been most successful in areas where an expert's judgement and experience are important in decision making for repetitive tasks. Many reviews and symposia proceedings have been published that survey expert systems applications for the construction industry [13–17]. The volume of published literature written between 1985 and 1989 attests to the perceived importance of expert systems technology to the construction industry. Now it is time to reflect on these experiences and assess their impact on real-world problem solving. Growth in the application of the technology will occur due to the existence of more efficient development tools and reduced development time. Also, recent successes in the business community will influence the acceptance of the technology for engineering applications.

In order to provide a better understanding of how expert systems have been applied to construction industry applications, the remainder of this section will summarize the areas and the role of expert systems.

3.1 Design applications

AASHTO BRIDGE RATING SYSTEM

The YACHT Bridge Rating System is designed to manage input data and existing database information and generate a bridge design. The system is developed to aid bridge engineers by rating simply supported highway bridges with reinforced concrete decks and prestressed concrete I-beams.

Methodology. The system comprises two sub-systems developed in parallel. They use a database to store knowledge from experts and the YACHT bridge rating provisions. The system uses forward-chaining inference within the database. Linear and nonlinear finite element models are included in the system and are used to produce a bridge design when a search of the database is exhausted with dissatisfaction about the rating quality. The systems represent a 2-level approach to the problem solution. The end user first provides a method of rating, then the system responds with a conclusion according to that method. Knowledge contained in the system is compared with past case knowledge.

The expert system was developed at Lehigh University and is written in structured Fortran to run on a Control Data Corporation mainframe computer.

State of project. The system is an operational prototype. Future versions will include updated databases.

References [14, 18].

BETVAL

BETVAL is a rule based expert system that provides advice on the selection of ready mix concrete for the job site. The purpose of the system is to assist construction site personnel in choosing the type of fresh concrete ordered from the ready mix concrete plant.

Methodology. Recommendations provided by the system are based on three areas of knowledge: 1, the compressive strength class and appropriate concreting techniques (e.g., curing, heating and heat treatment; 2, concrete consistency value based on the type of structure and the production equipment; and 3, recommendations on choosing the maximum size of aggregate.

State of project. BETVAL is one of several knowledge based systems developed at the Technical Research Centre of Finland (VTT). The system was developed using Insight2+ and uses an IBM PC/XT or AT computer. It is a demonstration prototype system that is being used primarily as a learning tool. Increasing the knowledge base for BETVAL would be required before it could be used as a production system.

Reference [19].

COMIX

COMIX is a rule and frame based knowledge based system that gives recommendations on the design of concrete mixes. The system is designed to be used by concrete technologists, design engineers, and consultants.

Methodology. COMIX first computes the amounts of cement, coarse aggregate and sand for 1 m^3 of concrete. The mix design is based on the New Zealand code 'Specification for Concrete Construction'. The system relates the type of structure to the consistency and the placement method. The system also recommends a water/cement ratio from a specified strength and calculates the amount of cement. The volume of coarse aggregate and sand is finally calculated and the masses of the components of the concrete mix are calculated and displayed.

State of project. The system was developed at Central Laboratories in New Zealand. The knowledge contained in the system represents expert information from a resident authority. Changes are being made to the system to extend the knowledge base to include revision of cement types and their strength factors.

Reference [20].

CONCEX

CONCEX is a knowledge based expert system designed to assist in the quality assurance of concrete at the construction site. The system seeks to evaluate factors affecting the concrete quality, applies tests at various ages to predict quality, and provides an easily accessible method of consultation and explanatory reasoning to the user.

Methodology. The knowledge base for CONCEX represents information obtained from books, journals, manuals and experts in the field. The system consists of five modules: 1, calculate concrete strength; 2, mix design and properties; 3, diagnosis of slump or air content; 4, compressive strength prediction; and 5, compressive strength prediction at various ages. CONCEX was developed at Rutgers University, using the RuleMaster expert system development tool. The knowledge is represented in IF-THEN production rules. Programs written in C and Fortran are embedded in CONCEX. These programs perform numerical calculations needed for the expert system. The expert system operates on IBM PC microcomputer systems.

State of project. CONCEX is currently at a development stage

Reference [6].

CONCRETE MIX DESIGNER

Concrete Mix Designer is a rule based expert system designed to provide information on trial mix proportions of concrete. The expert system knowledge is represented as IF-THEN rules that are grouped together as 'frames'. Each frame represents a component of the concrete, such as amount of coarse aggregate, and includes an expert system goal. The system is designed to serve as a tool for engineering students and practising engineers.

Methodology. Concrete Mix Designer uses the absolute-volume method to determine the proper proportions of ingredients. The knowledge contained in the system was obtained from The American Concrete Institute, Publication SP-1 and a Portland Cement Association publication. The system determines the following properties of the cement: 1, appropriate slump; 2, water/cement ratio; 3, amount of air content; 4, amount of coarse aggregate; and 5, amount of dry sand. The user specifies the strength of the concrete, type of structure, and exposure condition. The system then attempts to derive conclusions based on its knowledge. Conclusions in the form of text are presented to the user. Graphics and tutorial options may be selected to substantiate the knowledge and provide explanatory information.

State of project. Concrete Mix Designer is a prototype expert system that executes on a personal computer. The system was developed at the University of Miami in the Department of Civil and Architectural Engineering. The system was developed using the Personal Consultant Plus expert system shell. Also, computer programs were written in Basic to provide question and answer capability. These programs interface to the expert system knowledge base and provide modularity.

Reference [21]

CONTEC^{ES}

Contec^{ES} is an expert system for the diagnosis and treatment of deteriorated concrete structures. An object-oriented and rule-based expert system shell has been used for the implementation. Additional functions have been created to further facilitate user access. An extensive set of digital photographs and graphics are part of the knowledge base. These figures are available dynamically according to the state of the program flow. A prototype of Contec^{ES} which will be able to identify thirty different deteriorating actions on concrete surfaces will be completed in early 1995. Approximately one thousand rules will constitute the knowledge of relations between actions and their effects. The latest knowledge on concrete technology has been gathered from different sources and is implemented in the program's knowledge base. Information on the essentials of the deterioration process mechanisms are considered as well as additional information of lesser significance. The selection of repair measures and surface treatment according to German guidelines is already possible at the present stage. As and when they become available, models on the development of deteriorating processes will also become part of the program. For instance, the progress of carbonation will be estimated by considering material characteristics and data related to the structure's environment. Contec^{ES} executes on personal computers and runs in 'Windows'.

Reference [22]

DURCON

DURCON is an expert system that gives recommendations on the selection of concrete constituents for the following durability areas: corrosion, freeze–thaw, sulfate attack, alkali–aggregate reaction. The system also recommends the water/cement ratio and amount of cover for different environments. It was developed to provide expert knowledge for specifiers of concrete.

Methodology. The embodied knowledge of DURCON represents the American Concrete Institute 'Guide to Durability of Concrete', ACI 201.2R-77, and expert knowledge from ACI Committee 201 members. The approach taken in the development of DURCON was to divide the knowledge into four sub-systems, each representing an area of durability. The user of the system first selects the durability area, then answers questions related to the types of exposure, and concrete constituents such as aggregate size, and admixture.

DURCON was developed originally in the conventional programming languages of Fortran and Pascal. It was later converted to the Insight expert system shell, and in 1988 upgraded to the Level5 PC shell. The shell environment provided an improved method for knowledge enhancement by separating the knowledge from the inference (logic) procedures. DURCON is designed to run on an IBM PC/XT/AT using the DOS operating system.

State of project. The system has been distributed to ACI constituents for critique. An ACI 201 task group is currently revising the system to include new knowledge from the revised ACI 201 guide.

Reference [5]

EKSPRO

EKSPRO is a knowledge based system to assist architects in designing the thermal, illumination, occupational and usage patterns for buildings. It integrates CAD information with databases and building code regulations. The goal of the system is to select the layout, materials and equipment and their location to optimize the thermal comfort and lighting.

Methodology. EKSPRO consists of three levels of operation. The end user first selects a configuration from which all desired occurrences are brought to the first level. Within this level, lighting sources, materials, and ventilation conceptual objects are stored. The configuration generated in level 1 is then evaluated at level 0. Level 2 is designed to perform calculations as necessary during level 1. A major objective of EKSPRO is to reduce conflicts in design between designers and engineers. The main focus is to improve architectural design related to energy savings and thermal comfort.

EKSPRO runs on a PC/AT/MS-DOS Vaxmate microcomputer. The system is written in Prolog and Microsoft Pascal and uses special interface routines developed using Scribe Modeler. A 2 colour monitor system is used with Desqview windows to display CAD drawings.

State of project. The system was developed at the Technical University of Denmark, for Cenergia A/S where is it currently being used. Desired enhancements expressed by the end users include the addition of static structure calculations, building acoustics, building maintenance costs and selection of colour for walls.

Reference [23].

ESCON

ESCON is a rule based expert system designed to model the production of conventional concrete. The objective of the system is to improve the quality of concrete by minimizing mistakes in batch and mixing procedures. The system is designed to provide an understanding of concrete batching and mixing methods for new and inexperienced personnel.

Methodology. The structure of ESCON can be divided into two major parts: 1, batching and 2, mixing of concrete. Recommendations related to batching include: on-site and off-site; volume batching and weight batching; concrete quality; user selected equipment; and production rates. Recommendations related to mixing include the mixing method and quality control of the mix (e.g., cement balls, head packs, overmixing).

State of project. ESCON is currently in a development state. It is being expanded to include additional knowledge related to concrete operations, like transportation, finishing and curing.

ESCON was developed using the 'Savoir' expert system shell. The system represents a joint effort between Eastern Mediterranean University, Famagusta, Cyprus, and Loughborough University of Technology, UK.

Reference [24].

SLABFORM

SLABFORM is a rule-based expert system designed to assist the designer/planner select a horizontal formwork system for concrete buildings. The goal of the system is to offer recommendations on the optimum formwork based on the building shape, site characteristics, and available resources. Users of the system are asked multiple choice questions. The system can be used for the whole building or part of a building that has repetitive features.

Methodology. SLABFORM's knowledge base was developed through interviews with experts. The knowledge includes formwork systems designed for slabs or floors. The types include: 1, conventional wood systems; 2, conventional metal systems; 3, flying truss systems; 4, column-mounted shoring systems; 5, tunnel formwork systems; 6, joist-slab formwork systems; and 7, dome formwork systems. The output of SLABFORM consists of the rated formwork types based on the user's response to the questions. Each type is rated from 0 to 10, zero being the least suitable and 10 the most suitable. Any score above 6 indicates a reasonably suitable system.

SLABFORM was developed using the Exsys Professional expert system shell program and is designed to run on a microcomputer.

State of project. SLABFORM has been field tested and is in use by contractors as a training tool.

Reference [25].

3.2 Planning and management applications

ADVISORY SYSTEM FOR SITE MANAGERS

This advisory system is designed to assist construction site managers and foremen in prior planning and in daily routine tasks. The goal is to systematize the process of decision making. The system advises on such tasks as supervising incoming and outgoing information, costs, and technical problems of a site; also it warns of impending problems. The system uses programs to perform calculations for data intensive tasks, and expert systems to obtain an expert's experience. The topics covered thus far by the advisory system include: 1, crane disposition; 2, construction crew scheduling; and 3, concrete plant dimensioning.

The expert system shell 'Twaice' was used to develop the expert system. The system runs on a minicomputer.

State of project. The system is a developmental prototype system that has been tested for small jobs. Work has begun on rewriting the system in Smalltalk V for a personal computer. The new system will include a cost model, a resource model and an administrator model.

Reference [26].

3.3 Diagnostics, repair and rehabilitation

AMADEUS

AMADEUS is a rule-based expert system for assisting building inspectors during emergency post earthquake damage assessment. The system records field inspection data and makes recommendations concerning the safety of buildings that have been subjected to earthquake damage. It provides a detailed survey and evaluation of the seismic damage to masonry structures.

Methodology. AMADEUS gives recommendations regarding usability, severity of damage and habitability of structures based on qualitative measures of safety of a building under inspection. The recommendations are classified as high, uncertain, or low risks. The expert system attempts to achieve its goal and sub-goals involving the following categories: 1, geotechnical situation of and around the building; 2, state of the structural system; 3, hazards due to non-structural elements; and 4, danger inducted on the building by its non-structural components. The system is interactive and uses information provided by the end user to give recommendations. The system improves the questionnaire-type form method. It guides the user in reasoning about the situation by focusing on important factors under given conditions, and ignores irrelevant details. The end user may ask why and how questions, and input values may be changed during the course of an interactive session. Also, uncertainty factors are used to obtain an inspector's confidence in this response.

AMADEUS is primarily a rule-based system. Knowledge is represented in parameters (input information), rules, and frames. The system was developed using 'PcPlus', a Lisp-based expert system development tool. It runs on a personal computer. The database component of the system is stored in the dBASE III+ format.

State of project. AMADEUS is a prototype system. It was tested following an earthquake that occurred in Barrea, Italy. The system is expected to be developed further as additional knowledge becomes available.

Reference [27].

BRIDGE RATING EXPERT SYSTEM

The Bridge Rating Expert System is designed to provide a serviceability rating for bridge structures in Japan. The system was developed to assist engineers in assessing the condition of various bridge elements. The system addresses serviceability, durability, and load capacity, and incorporates knowledge from experts, incorporates probability theory (for subjective observations), and has a relational database component.

Methodology. There are two basic components to the expert system: 1, the Bridge Rating Expert System; and 2, a fuzzy relational database. These two components contain inference rules for the system, and knowledge about the structure, respectively. The expert system addresses reinforced slab and girder components of bridges. The knowledge domain includes information on the following conditions: 1, cracks; 2, corrosion of steel; 3, deflection of girders; and 4, dynamic properties of slabs. The goal of the system is to rate the condition of the bridge, in one of five categories, from safe to dangerous. The system uses Dempster and Shafer's theory of basic probability to determine the appropriate category. The fuzzy set relational database was developed from information contained in questionnaires received from highway staff. This information represents opinions based on observations made by practising engineers. The system uses both forward and backward chaining inference. The system performed well during tests of three bridge sites.

The expert system was developed using the computer languages Prolog and C. dBASE II was used to manage the database. The system executes on an NEC personal computer system.

State of project. The Bridge Rating Expert System is currently in the development stage, and is being expanded to include data from new structures.

Reference [28].

CRACK

CRACK is a rule based expert system designed to diagnose the causes of cracking of cast-in-place concrete structures, namely, tunnels, tanks, and foundation walls. The system also recommends methods for controlling and repairing cracking. The system contains Chinese design codes and specifications for constructing concrete structures.

Methodology. CRACK knowledge and inference is represented in four modules and two external computer programs. Their functions are to check for design and construction deficiencies, diagnose cracking, evaluate the risk, and recommend repair methods.

The CRACK design checking capabilities are based on the Chinese design codes and specifications. The minimum requirements on grades of concrete, steel reinforcement, and limitations on stress concentration for the construction codes are represented in the expert system rules. An external computer program is used to input information about a structure's characteristics, environment, and operation. These data are later used by the diagnostic module to calculate stress, temperature, and crack dimensions.

The CRACK construction fault-checking module checks against Chinese construction codes, specifications, and standards. This module addresses the effect of construction on concrete constituents, mix, operation, vibration, curing and formwork.

The diagnosis module of CRACK attempts to determine the stress condition. This module uses information from the user obtained in the acquisition module. It describes the crack age, pattern, location, direction, depth, length, and width.

The repair and rehabilitation module of CRACK evaluates the consequences of the cracking and recommends a repair method. The recommendations are based on the cause and characteristics of the cracking, load factors, and crack history.

As stated previously, the CRACK knowledge base was developed from the Chinese design and construction code, and includes concrete diagnostic expert knowledge from the field. The system was developed using an expert system shell and the programming language Fortran for external calculations.

State of project. CRACK is a developmental prototype system and is undergoing field testing.

Reference [29].

CRACKS

CRACKS is a rule-based expert system designed to provide inspectors and facility managers with conclusions about the probable cause of cracks in concrete. The system deals with primarily non-structural cracks in concrete elements, such as slabs, columns, thick sections, and thin walls. The CRACKS knowledge base is in three parts: 1, facts, and rules of thumb; 2, database information; and 3, digitized images.

Methodology. CRACKS attempts to identify the probable cause of the crack by first requesting the age of the observed crack in the element. Drawings and photographs of actual failures are used to provide the user with a visual display for identification and confirmation. The system currently deals with cracks at early ages, after hardening and when the age of the crack is unknown. The system relies on the user's visual inspection and uses knowledge from experts in the field of concrete crack diagnostics to derive its conclusions. When a goal has been reached, the system displays the probable cause (e.g., plastic shrinkage, 'D' cracking, etc.). Also, examples are displayed of typical crack patterns associated with the specific cause. The images help the user in confirming the conclusion reached by the expert system.

CRACKS was developed using the Level5 PC expert system shell. An IBM PC/XT/AT personal computer or compatible is recommended for its use. Custom computer programs were written in the programming language C. These programs provide explanatory facilities, image display, and utility functions.

State of project. CRACKS is a developmental prototype system developed at the National Institute of Standards and Technology. The system is currently available for review and comment. Additional knowledge covering other types of distress (e.g., spalling, disintegration, etc.), and recommendations on tests to confirm system hypotheses would be needed to make CRACKS an operational system.

Reference [30].

EXPEAR

EXPEAR is a knowledge based system designed to assist highway engineers in evaluating and rehabilitating concrete pavements. EXPEAR is designed to simulate a consultation between a highway engineer and a pavement expert. The system has the following capabilities: pavement evaluation; identifying type and some general causes of deterioration; selecting rehabilitation techniques and strategies; and predicting performance of rehabilitation options. Three pavement types are considered by the system: 1, jointed reinforced concrete pavement (JRCP); 2, jointed plain concrete pavement (JPCP); and 3, continuously reinforced concrete pavement (CRCP).

Methodology. EXPEAR maintains the most comprehensive knowledge base on concrete pavement evaluation and rehabilitation available. EXPEAR is a highly data driven system that uses data and knowledge from pavement studies dating back to 1985, and from experts in concrete pavements. The system deals primarily with pavement performance, and uses predictive models to show future pavement performance. EXPEAR uses the following procedures to obtain its recommendations: 1, project data collection (present condition); 2, prediction of future condition without rehabilitation; 3, physical testing; 4, selection of main rehabilitation approach; 5, development of rehabilitation strategy and performance prediction; 6, cost analysis of alternatives; and 7, selection of preferred rehabilitation strategy.

EXPEAR integrates both diagnostic (evaluation) and design (rehabilitation) activities for pavement management. The system is intended to be used on Interstate-type divided highways with two lanes in each direction and either asphalt or concrete shoulders. The major problem areas covered by EXPEAR include: 1, structural capacity; 2, drainage; 3, foundation stability; 4, roughness; 5, concrete durability; 6, skid resistance; 7, transverse joint condition; 8, longitudinal and transverse joint construction; 9, load transfer; 10, slab support; 11, joint sealant reservoir design; and 12, shoulder condition. Concerning durability, EXPEAR addresses only D-cracking and alkali–aggregate reactivity. It does not provide recommendations on the selection of materials.

EXPEAR is written in Pascal and executes on an IBM or compatible personal computer. Adapting EXPEAR to execute in an expert shell environment would enhance the maintenance of and future enhancements to the system.

State of project. The current version of EXPEAR is 1.3. The system was developed initially for the Federal Highway Administration. Support has continued for system development through the Illinois Department of Transportation. EXPEAR is an operational system.

Reference [31].

HWYCON

The Highway Concrete (HWYCON) expert system is designed to assist highway departments involved in diagnostics, selection of materials, and repair and rehabilitation activities to make better decisions about concrete structures. The diagnostic components of HWYCON, called Concrete Pavement-Diagnostics (CONPAV-D) and Concrete Structures-Diagnostics (CONSTRUC-D) help identify distresses and give conclusions as to their cause(s). It deals with distresses that occur in concrete pavements, bridge decks and sub-structures (walls, columns, etc.) It is intended for use by inspectors and engineers. HWYCON's Concrete Materials (CONMAT) gives recommendations on the selection of materials for the design of durable concrete in corrosive, sulfate, freeze–thaw, and alkali–aggregate environments. Also, new technologies for early opening of highway structures after repair, permeable bases, and recycling concrete are included. CONMAT is intended for use by concrete specifiers. HWYCON's third module, called Concrete Pavement-Rehabilitation (CONPAV-R) gives recommendations on materials and procedures for repair and rehabilitation methods. These include full and partial depth repair, bonded and unbonded overlays, and diamond grinding and milling. CONPAV-R is intended for use by decision makers involved in the repair and rehabilitation of concrete pavements.

Methodology. The HWYCON knowledge base was developed using the following resources: 1, expert team; 2, published literature; 3, field distress guides; 4, American Concrete Institute guides; 5, ASTM and AASHTO guides; and 6, results from Strategic Highway Research Program (SHRP) research programs. HWYCON's knowledge base includes digitized photographs, drawings, facts, and rules-of-thumb, explanatory information, and tables. To use HWYCON, the user answers questions about the structure and its environment. Visual information helps the user to identify distresses and answer questions better.

The system was developed using the Level5 Object expert system shell program. It is designed to run on microcomputers: desktop and also portable computers for field use.

State of project. HWYCON is an operational expert system being used by US state, local government and city transportation departments. Three thousand copies of the system have been distributed.

Reference [3].

PAVEMENT EXPERT

PAVEMENT EXPERT is a rule based expert system designed to assist inspectors and engineers in condition assessment and making field observations on concrete pavements. The system automates the process of making observations, and produces a pavement rating to support decision making.

Methodology. The system is based on the manual Pavement Condition Rating (PCR) index for pavements. It considers incidence, severity, and the extent of range of distress for each road section. Twelve distresses are analysed by the system. These distresses include the following categories: surface deterioration, patching, pumping joint spalling, and cracking.

PAVEMENT EXPERT involves several procedures: 1, initial inspection and data logging; 2, review observations; 3, detailed inspection; and 4, review PCR indexes. During the initial inspection and data logging phase, a mobile unit and portable computer are used to deal with visual observations of the pavement condition. From this phase, a preliminary evaluation is provided to the user. A graphical display aids the user in reviewing and identifying the observed distresses. A detailed inspection is then performed to enable the PCR index to be determined. During this process, the user maintains a dialogue with the system. The system identifies the distressed pavement sections for the user. A help facility can be used to obtain information summarizing the distresses, give details, describe the current stage of the evaluation and start and stop the inspection. The final step in the system is to review the results and make adjustments in pavement section boundaries. The results are summarized and the PCR and structural design indexes are computed.

The Savoir expert system shell was used to develop the expert system. Computer programs written in Pascal were linked to the expert system. The programs were used to represent procedural logic. The system executes on an IBM or compatible personal computer.

State of project. PAVEMENT EXPERT is an operational prototype system, and is being used by highway staff in the UK.

Reference [32].

PAVER

PAVER and Micro PAVER are knowledge based or decision support systems for pavement management. PAVER is the mainframe version, and Micro PAVER executes on a microcomputer. PAVER has been developed to optimize the use of funds allocated for pavement maintenance and rehabilitation. PAVER and Micro PAVER can be used to manage roads, streets, parking lots, and airfield pavements. The PAVER systems were developed to provide engineers with a systematic approach for determining maintenance and rehabilitation needs and priorities for pavement management.

Methodology. The PAVER system is based on the Pavement Condition Index condition survey and rating procedure developed at the US Army Construction Engineering Research Laboratory. Although PAVER was developed for use at military installations, it is useful for municipalities, airports, universities, and consultants. Requirements for using PAVER are to develop a network inventory. This involves the establishment of a database to identify and describe the pavement, condition survey results, construction and repair information, and surface type. Once the network has been established, the user can perform a 'network analysis' or project analysis. Network analysis can be used for projecting long term maintenance and rehabilitation needs. Project analysis is for current year or near-term needs.

The network analysis results in a projected condition, budget scenario, and work plan. This can be used subsequently to produce an actual budget and priority list for projects. Project analysis provides the user with detailed condition survey information plus feasible alternatives for maintenance and rehabilitation.

Data collection for PAVER has been implemented using condition distress sheets to standardize and facilitate the process. Reporting capabilities of the system include: inventory, inspection scheduling, pavement condition index frequency, budget condition forecasting, and network maintenance.

The pavement condition survey is a key component of the PAVER system. During this operation, the distress, severity, and condition index are determined, and it is performed through a visual inspection of random units of the pavement inventory (sections). Once the condition survey has been recorded in the database, the various network analysis and project analysis reports can be generated.

PAVER has been developed for a mainframe time-sharing computer. It can be accessed via telephone lines using a computer terminal and modem, or personal computer. Micro PAVER can be purchased to execute on an IBM PC. The programming languages Fortran and C were used to develop computer code for PAVER and Micro PAVER. Data file structures are compatible with the RBASE database management system.

State of project. The systems are revised frequently to incorporate new techniques for pavement management. They are considered operational systems. Version 2.12 is the current version of PAVER and Version 3.0 is the current version of Micro PAVER. These include increased capabilities for family analysis curves (graphical representations of related pavement sections), reporting, and file export.

Reference [33].

REPCON

REPCON is a rule based expert system designed to help engineers to judge the condition of damaged concrete structures and to recommend repair proposals. The system is based on the German Association for Concrete and Reinforced Concrete regulations.

Methodology. The user of REPCON first describes the structure, structural parts of the building, and information concerning the damage. The knowledge base considers damage to the structure due to carbonation, chlorides, and other chemical causes. REPCON then attempts to analyse the damage and produce a repair proposal. Data files are interfaced to the expert system. These files contain information about the structure (its name, size, and type), a description of the damage and different repair strategies. The data files are used by the data management program to recommend the appropriate set of repair strategies. The expert system also utilizes pictures of typical damage to support the decision making process. Certainty factors are used in the system to deal with 'don't know' or 'uncertain' responses from the user.

REPCON was developed using the Personal Consultant Plus expert system shell. The system operates on an IBM PC or compatible.

State of project. REPCON is a developmental prototype system.

Reference [34].

4. FUTURE TRENDS

Future trends that will affect the development and use of expert systems will involve four key factors.

1. Complex knowledge (e.g., building codes, and mathematical models) will be integrated in many different forms. Visual information will become an increasingly important component to aid in the display of the expert system's knowledge. This will improve the usefulness of expert systems.
2. Improved interfaces to databases, computers, and neural networks will be included in expert system shell programs.
3. The need to provide expert systems access within local and world-wide network environments will be emphasized by developers. This will increase the use of expert systems on a much wider scale.
4. Future expert shell programs will be developed for a class of problems. For example, statistical programs and math libraries will be available for developers to integrate computational capabilities with high-level reasoning.

APPENDIX A

Glossary of expert system terms

backward chaining An inference method where the expert system starts with what it wants to prove and tries to establish the facts needed to prove it

certainty factor The degree of certainty with which a fact or rule is considered to be true

demon A forward chaining IF-THEN rule

domain knowledge An area of expertise or knowledge that deals with a specific application

expert system A computer program that contains knowledge about a specific domain together with inference procedures that indicate how to use the knowledge

facets Provides control over how the inference engine processes and uses class attributes

forward chaining An inference strategy that starts with known facts or data about a situation and infers new facts about the situation based on information contained in the knowledge base

frame A knowledge representation method that incorporates nodes and objects, which are defined in terms of slots

fuzzy set Information about a situation within a problem that is not known with certainty and is described as a true/false state, involving some degree of fuzziness. This fuzziness may be expressed as some number between 0 and 1

goal An intermediate or final objective which is established in the expert system (e.g., conclusion, recommendation)
inference engine That part of the expert system that operates upon the knowledge and contains the problem-solving capabilities
knowledge base That part of the expert system that contains what is known about a subject (e.g., an expert's knowledge)
knowledge engineer The expert system designer and builder who interacts with the experts
methods Procedures that are established by the developer to support class attributes
rule A method of representing a recommendation, directive, or strategy, in an IF condition THEN action form
shell An expert system building tool that provides programming, knowledge representation, and inference capabilities
slot An attribute of a frame: it may represent an object, concept or event

APPENDIX B

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